Implications for Future Research

Appendix I

Throughout this report we have attempted to accurately characterize and, where possible, quantify the major sources of uncertainties that affect our primary estimate of the costs and benefits of the CAAA. In many cases, these uncertainties are the result of gaps in data or methods that might be addressed through additional research. In this Appendix, we provide a summary of important areas for new research which, if carried out, have the potential to increase accuracy and reduce uncertainty in future assessments.

Overview

The uncertainties in the primary estimates and the controversies which persist regarding model choices and valuation paradigms highlight the need for a variety of new and continued research efforts. Based on the findings of this study, the highest priority research needs are:

- Improved emissions inventories and inventory management systems
- Improved tools for assessing the full range of social costs associated with regulation, including the tax-interaction effect
- A more geographically comprehensive air quality monitoring network, particularly for fine particles and hazardous air pollutants
- Development of integrated air quality modeling tools based on an open, consistent model architecture
- Increased basic and targeted research on the health effects of air pollution, especially particulate matter
- Continued efforts to assess the cancer and noncancer health effects of air toxics exposure
- Development of tools and data to assess the significance of wetland, aquatic, and terrestrial ecosystem changes associated with air pollution
- Continued development of economic valuation methods and data, particularly valuation of changes in risks of premature mortality associated with air pollution

We discuss each of these research needs in greater detail in the sections that follow.

Emissions Modeling

Our analysis of emissions suggests several areas of research that could improve emissions data and modeling tools. The overall importance of ambient particulate matter estimates to the results of this analysis makes improved modeling of particulate matter and precursor emissions a high priority. Ambient monitoring of particulate composition, for example, indicates that particulate matter of crustal origin (e.g., from agricultural tilling, construction, and wind erosion) may be over-represented in our emissions inventories. As we discuss in the report, one possible explanation for this apparent inconsistency may be the extent to which these emissions are transported beyond their point of emission. Some preliminary evidence suggests that the mobility of a large fraction of these particles may be relatively limited, but further research is needed to confirm this hypothesis.

Comparison of emissions inventories with monitoring data also suggests that our inventory may underestimate the organic and elemental carbon fraction of directly emitted particulates, particularly in urban areas. In this case, it is more difficult to assess the potential sources of underestimation. One hypothesis is that current emissions estimation tools may underestimate organic particulate emissions from mobile sources. Continued research into emissions rates for mobile sources could yield increased accuracy for particulate emissions. Additional tailpipe emissions studies may be needed, and emissions estimation techniques need to be developed to better reflect the results of those studies. In general, continued research to better reconcile monitoring data on the composition of ambient particulate matter on the one hand, with emissions estimates for primary and secondary sources of particulate matter on the other hand, should help in improving our ability to predict changes in fine PM concentrations.

One other emissions uncertainty that could be reduced by additional research involves volatile organic compound (VOC) emissions. Estimates of VOC emissions tend to be highly variable -- in the summer months especially, they can be closely linked to variations in temperature. As ambient ozone modeling becomes more sophisticated, however, better temporal and spatial resolution of VOC emissions inventories may be needed to take advantage of the increased capabilities of air quality models to process more highly resolved data.

In a broader sense, our current inability to quantitatively characterize and carry through the analysis the impact of key uncertainties in emissions estimation may give the misleading impression that these uncertainties are less important than other quantifiable sources of uncertainty. For example, the statistical simulation modeling analysis we present here reflects only quantifiable sources of uncertainty in the concentration-response and economic valuation steps of the analysis. Uncertainties in emissions estimates, however, may be among the most important in the entire analysis. Emissions estimates are a critical first step in our approach, so errors in this step can magnify as we work through the subsequent steps of the analysis. One way to enhance the quantification of emissions estimation uncertainties in future assessments, and to reduce any potential errors of inconsistency with the subsequent air quality modeling steps, is to develop a tool that both integrates emissions and air quality analyses and provides a means to more cost-effectively perform multiple scenario analyses. The Models-3 development effort, described below, may provide a modeling platform that is more amenable to sensitivity testing of alternative emissions results.

Cost Estimation

The first prospective analysis relies on direct expenditure estimates to characterize the costs of the CAAA. As we state in the report, this approach probably does not represent a large source of error in our estimate of social costs, though there is some evidence it may provide conservative estimates. The direct cost approach does not provide information on other potential categories of impact that may be of interest, however, including total employment, employment by sector, capital accumulation patterns, and the pace of technological change. Additional cost-effective tools are needed to better estimate the secondary impacts of direct cost estimates for broad, programmatic assessments such as the section 812 series.

One potentially important area where research may enhance our ability to conduct broader assessments is development of computable general equilibrium (CGE) models that can be implemented in a resource-effective manner. The potential for introducing additional error when using such a forecasting tool, however, demands the model be capable of processing many scenarios of important economic inputs (e.g., alternative interest rate scenarios) to better bracket the range of future outcomes relevant to CAAA implementation.

A well-designed CGE model may also enhance our capability to estimate the effects of the tax-interaction effect, both on the cost and the benefit side. Additional empirical work will also be needed to confirm that the magnitude of the effect estimated in the current literature, which is largely confined to the electric utility sector, is applicable for other economic sectors where the competitive dynamics and capital-intensity of production may differ from those in the electric utility industry.

Air Quality Modeling

Our current limited ability to disaggregate the overall benefits of the CAAA is largely attributable to the complexity of the relationships between changes in precursor emissions and the ambient concentration outcomes. For example, nitrogen oxides are precursors of both fine particulate matter and ozone, and their presence in the atmosphere also affects the conversion of sulfur dioxide to fine particles. In addition, while low levels of nitrogen oxides can contribute to elevated ozone concentrations, very high levels of nitrogen oxides, in the right combination with VOCs and certain meteorological conditions, can suppress ozone concentrations. These complex interrelationships among pollutants affected by the CAAA, coupled with the national scope of the analysis conducted here, demand the use of an air quality modeling technique that accurately reflects the complexities of atmospheric chemistry. Estimating the incremental impact of various combinations of emissions changes would require the repeated exercise of the model for each alternative set of emissions scenarios of interest.

The models we chose for this analysis, while they represent the current state of the art in modeling atmospheric chemistry, are difficult and expensive to run for a wide range of scenarios. To improve our ability to disaggregate the benefits of the CAAA, we need a fully integrated air quality modeling and emissions input system that accounts for the full range of pollutant interactions and relevant atmospheric chemistry. The current Models-3 effort holds promise in this area, but must be adequately funded to achieve these goals. Pursuit of a fully integrated modeling system also holds promise for generating more accurate ambient particulate matter estimates. The current best modeling systems for this purpose provide estimates based solely on changes in the concentrations of sulfate- and nitrate-derived particles, with limited abilities to assess changes associated with organic precursors of fine particles. Gaining a good understanding of organic particle formation may also be an important goal in better characterizing the full range of impacts of efforts to control air toxics under Title III. In addition, a more cost-effective air quality modeling tool may also enhance our ability to conduct comparative analyses and explore the sensitivity of air quality modeling and emissions estimation outcomes to alternative assumptions and modeling paradigms.

Improvements in exposure analysis might also be made with additional research into techniques for extrapolating the results of monitor-based analyses to unmonitored areas. In particular, we suggest further exploration and development of methods that base extrapolation on the causes of ambient air quality (e.g., local land use, emissions characterizations, meteorology, and terrain), rather than the outcomes of air quality modeling (e.g., simple extrapolation of air quality concentrations). In the course of developing this analysis, we began development of such an approach, termed the “homology mapping” technique. Continued development of this tool could improve the accuracy of our estimates in future analyses for those areas that are distant from monitors.

Human Health Effects Estimation

The results of our analysis clearly highlight the importance of the link between premature mortality and air pollution. The wide range of current research on this link, including the several short-term and long-term cohort studies, provides a strong basis for establishing that particulate matter contributes to premature mortality among the exposed population. The existing studies, however, are limited by the availability and resolution of air quality monitoring data, data on the characteristics of exposed populations, and, in the case of the long-term studies, extensive time-series of these data. The continued enhancement of our air quality monitoring network, particularly for fine particles, is critical to the better understanding of the relationships between fine particles and human health effects. Developing long-time series of fine particle data will take time, however. In the meantime, it is important to continue efforts to better isolate the separate and joint impacts of ambient pollutants on premature mortality, including better resolution of the incremental impacts of ozone, carbon monoxide, nitrogen oxides, sulfates, and particles in the ultrafine and fine fraction, as well as the coarse particles within PM_{10}.

In addition, the sensitivity analyses presented in Appendix D show that a resolution of competing alternative hypotheses about the presence and potential time period of a lag in the incidence of premature mortality following exposure may be important. Although in our judgment assuming a distributed five-year lag period may be warranted, there is no scientific basis for either the assumption of a lag or for determining the appropriate time period. We believe it will continue to be important to evaluate the existing evidence and develop new studies to clarify the extent to which the premature mortality outcomes reflected in the existing epidemiological literature ought to reflect a lag period between exposure and the mortality effect.

For premature mortality and for other health effects, our analysis is based on the premise that the available literature provides broadly applicable characterizations of the relationships between exposure to air pollutants and the incidence of health effects. We use the results of available studies on a national basis, although in many cases the underlying literature may be based on analysis of the concentration-response relationship in a particular region. It is possible, however, that region-specific factors may play a role in the results of these studies. For example, the composition of air pollutants such as particulate matter varies by region, and it is possible that other, perhaps unobservable factors may have a synergistic or mitigating effect on the incremental incidence of health effects. The literature on air pollution's influence on health is not yet broad enough for us to implement a regional approach to health effects estimation. As the literature base develops, however, a regional approach may be an option for future assessments. In the meantime, it is important to continue to develop a broader base of regional estimates of the effects of multiple pollutants on key health outcomes, including mortality, chronic bronchitis, and hospital admissions, to better reflect the impact of potentially important regional differences in the composition of particulate matter and other human health stressors. Expanding the current literature base may also provide a better means for evaluating the effects of air pollution on sub-populations of individuals, such as children and the infirm, that may be of increasing importance in the Federal government regulatory effort.

Evaluation of the Effects of Air Toxics

In order to develop a meaningful estimate of the benefits of air toxics controls for future 812 Prospective analyses, we must address existing knowledge gaps and other methodological barriers that prevent more realistic analyses of the benefits of air toxics control. We have already begun developing a detailed research plan for improving the assessment of air toxics in future prospective analyses. For example, EPA has agreed to sponsor workshops that bring together experts in toxicology, exposure and risk assessment, and economics with the goal of establishing a framework for air toxics benefit estimation. In establishing such a framework, we will need to address issues and research needs related to estimating both air toxics exposure and the hazard posed by individual air toxics.

Exposure-related research needs include both the development of a database of air toxics measurements and the extent to which individuals, on average, would be exposed to the measured concentrations. To address the first issue, we plan to explore the potential for compiling a database of air toxics data from established state air toxics monitoring networks. We also plan to explore design options for the "super-site" monitoring programs that will permit them to be exploited to better understand exposure to air toxics linked to key health effects categories, and to improve the performance of ambient concentration modeling efforts.

More generally, there is a need to continue to pursue research aimed at the following goals: (a) improving methods to estimate current levels and future changes in acute and chronic ambient exposure conditions nationwide; (b) evaluating the full distribution of concentration-response relationships linking exposure and health outcomes, with the goal of providing a better estimate of the central tendency of the relationships to support primary benefits estimation; and (c) tailoring economic valuation methods for the broad array of potential serious health effects such as renal damage, reproductive effects and fatal and non-fatal cancers, including accurate characterization of the impact on valuation of latency periods for these effects, where applicable.

Ecological Effects Estimation

The research needs for future analysis of the CAAA's ecological benefits can be viewed from two perspectives. The first is the valuation of additional first order, acute ecological effects that change the level of service flows society receives from ecosystems, and the second is assessing and valuing the broader changes to the structure and function of ecosystems. Our analysis reflects the state of the current data and methods in this area by characterizing and quantifying ecosystem service flows affected by air pollutants, but many gaps remain. Pursuing a strategy of enlarging the array of quantified service flows would entail further development of economic models and collection of data. However, notably absent in this report is quantitative treatment of the changes of ecosystem structure and function that do not measurably affect the provision of service flows to society, such as nutrient cycling, species composition, and the resistance and resilience of ecosystems to disturbance. Because many ecological benefits of the CAAA fall into this category, future research could adopt a strategy of developing analytic tools to assist in the valuation of these impacts.

Our current analysis suggests several ways we can enhance the comprehensiveness of coverage for potentially important service flows. For example, while we can develop estimates of the changes in mercury emissions attributable to CAAA provisions, and there is an extensive literature on the effects of mercury in ecological systems, there are great uncertainties in estimating the fate and transport of incremental increases in airborne mercury emissions. The persistence of this element, the potentially long recovery times for ecological systems contaminated with mercury, and the potentially global scale of mercury transport suggest that overcoming this barrier will be challenging; however, existing tools may provide a good starting point for bounding analyses. Similar issues are present in assessing the ecological effects of air toxics. Some toxics are persistent in natural systems, can be attributed to multiple airborne and other sources, and have been accumulating in the environment for many years. Analyses aimed at characterizing effects at the watershed level, however, may be more successful in capturing many of the complexities of source-receptor relationships and receptor sensitivities than the national analyses we have traditionally pursued.

Analyses of nitrogen deposition in the current report are based on a displaced cost approach. The uncertainties and potential circularity of this approach limit its applicability to a subset of the aquatic systems susceptible to eutrophication. A more widely applicable and therefore more promising approach for future analyses will be an avoided damages analysis. To complete such an approach, however, further research is needed to better explain the dose-response relationships between increased nitrogen loads, thresholds of nitrogen loading that lead to eutrophication, and the ecological mechanisms that lead to the loss of service flows such as recreational and commercial fishing. Some recent analyses attempt to bridge this gap through the development of reduced form relationships between nitrogen loads and service flow disruption, but these types of approaches also have only limited applicability unless they can be shown to hold for long periods of time and across a wider range of marine environments, climate conditions, and species types.

In some cases acute impacts to ecosystems, such as the disappearance of game species from particular ecosystems or foliar damage to trees, attract the attention of the public and policy makers. Such acute impacts generally have effects that are observable and alter the provision of ecosystem services in a measurable way. Less often noticed are the ecosystem-level ecological impacts that change ecosystem structure and function but do not immediately affect service flows received from that ecosystem. By focusing on acute impacts it is possible to lose sight of ecosystem-level changes to structure and function that could eventually lead to large-scale impacts far greater in degree and geographic extent than the contemporaneous, acute effects.

Ecosystems generally maintain multiple interchangeable elements that may drive a particular process, as hypothesized by Odum (1985) for forest ecosystems and Howarth (1991) for aquatic systems. This allows for natural variation in these elements as well as long-term cycles in which some elements dominate over others. Explicit in the definition of ecological structure and function is the ability of an ecosystem to adapt to natural changes in its environment. When pollution affects ecosystem functions such as nutrient cycling, water filtration, biological diversity, and provision of habitat, it may also be precluding the system's ability to adapt and respond to change and perform these functions in the future. The ultimate effects of such changes in ecosystems are sometimes unpredictable in scale and nature. Ecosystems impacted by mankind may respond in a discontinuous manner around critical thresholds that are boundaries between locally stable equilibria (Common and Perrings 1992; Constanza et al 1993). Complexity in ecosystems prevents analysts from using linear methods to "add up" the discrete ecological effects of pollution.

Additional research is also needed to develop economic valuation methods that can adequately characterize the monetized benefits of maintaining ecosystem structure and function in their current states. Contingent valuation approaches may prove valuable, but the scientific basis for evaluating changes in ecosystems needs to be sufficiently advanced that analysts can construct plausible scenarios of alternative ecosystem outcomes for respondents to react to. To lay the groundwork for these efforts, there is an immediate need to identify the key attributes of ecosystems that are most valued by individuals. The results of those types of scoping analyses might be useful in targeting subsequent scientific and ecological research, with the goal of developing pilot analyses that integrate robust and realistic characterizations of the changes in ecological resources attributed to air pollution with careful economic valuation approaches to assess the value of avoiding those changes.

The isolation of service flows, while a useful interim tool for quantifying and monetizing the effects of air pollutants on ecosystems, may imply an oversimplified cause and effect relationship between pollution and the provision of the service flow. As our analysis suggests, often the service flow is affected by complex non-linear relationships that govern ecosystem structure and function. Pursuit of the short-term goal of enhancing our understanding of ecological effects on service flows may ultimately provide new insights into our understanding of these complex relationships. At the same time, we suggest that it will continue to be important to pursue methods to estimate the effects of air pollution on other ecological indicators of concern, including those that may not be directly linked to service flows, recognizing that accurate assessment of changes in nutrient cycling, water filtration, biological diversity, provision of habitat, and other valuable aspects of ecosystems may ultimately demand a broader view of these effects.

Economic Valuation

The importance of the economic valuation step in our benefits assessment is highlighted by our analysis of the influence of key variables on the overall range of uncertainty from our statistical simluation modeling analysis. Our analysis clearly shows that uncertainty in the measurement of the value of statistical life dominates the quantifiable uncertainty in our overall estimates. In addition, there remain several important non-quantified uncertainties in the use of labor market studies to value avoidance of environmental risks from air pollution. These uncertainties were also highlighted in the section 812 retrospective analysis report, and as a result many are currently being pursued as part of federally sponsored and independent research studies.

First, to the extent we must continue to rely on the value of statistical life (VSL) approach to value avoided mortality risks, we need more advanced methods for discerning an appropriate VSL from the extensive literature on this topic. The application of meta-analysis techniques may help us better understand the impact of important methodological and measurement choices that are made in conducting these studies, and provide a basis for narrowing the range of appropriate VSL estimates for environmental risk estimates. Second, we need to develop a better means for adjusting VSL estimates to address the key benefits transfer issues from the risk scenarios presented in existing studies to the specific mortality risk presented by particulate matter air pollution. Pursuit of this goal would include developing better adjustment techniques for differences in age, health status, and the risk context, including such attributes of risk perception as dread and the involuntary nature of environmental exposures.

Third, and perhaps most importantly, we need to develop a better literature basis for directly valuing the commodity provided by air pollution reductions, that is, reductions in the risk of dying prematurely or, put another way, changes in individual's survival probabilities. Several research efforts are currently underway that are attempting to directly value life extensions similar in magnitude to those provided by air quality improvements. These research efforts necessarily rely on stated preference methods, which in most cases are considered less reliable than the revealed preference estimates used as the basis for VSL approaches. Substantial analytic challenges remain in making the risk reduction scenarios presented to respondents clear and understandable to the lay person, but the results of this new work will need to be carefully considered for their implications for a new paradigm for valuation of mortality risk reduction.

Beyond the valuation of avoided premature mortality, there are several other areas of research that, if pursued, can enhance our ability to value the health outcomes of reductions in air pollutants. For example, we must develop a broader research base for valuation of avoided effects to children, including construction of an overall framework for considering the welfare and utility of children within the broader family context, to better characterize the effects of air pollutants to this important sub-population. It may also be fruitful to pursue the potential cost-effective advantages of developing a more flexible means of valuing health effects through health-state utility approaches. More research is needed to assess the trade-offs in accuracy and precision of these results with the advantages of a broader set of WTP estimates to apply to relevant endpoints (for example, to value the avoidance of hospital admissions).

Additional research is also needed to enhance our ability to value important welfare effects. Visibility continues to be one of the most important welfare endpoints for analyses of particulate air pollutants, but it would be useful if the literature base were periodically updated to better reflect the current state-of-the-art in stated preference technique. For example, an important research direction would be to pursue development of additional estimates for residential visibility valuation to corroborate those currently available, and develop insights into the potential for double-counting in application of the location-specific residential and recreational visibility valuation estimates. The literature on materials damage valuation is also in need of updating. We chose not to include an estimate for household soiling effects in our primary benefits estimates because of the age of the original research, its reliance on an older measure of particulate air pollution (total suspended particulates), and its reliance on outdated household expenditure data. Updating existing estimates of the effects of air pollutants on household soiling expenditures would be a relatively straightforward research project. Agricultural analyses could also benefit from a broader assessment of the crops potentially affected by ozone and other pollutants, and by the joint analysis of not only the damaging effects of some pollutants but also the yield-enhancing effects of others (e.g., nitrogen deposition).

The results of this first prospective analysis continue to suggest that our nation's investment in clean air has been a wise one. At the same time, we recognize that we should continue to assess the progress of the clean air program, as implemented under the Clean Air Act, to ensure that benefits are achieved in the most cost-effective means possible. Pursuit of the research goals outlined above will continue to enhance our ability to provide accurate and timely assessments of the costs and benefits of all provisions of the Clean Air Act.